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AN EXPERIMENTAL INVESTIGATION  
OF THE RESTART AREA RATIO  
OF A MACH 3.0 AXIS SYMMETRIC  
MIXED COMPRESSION INLET

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Cleveland, Ohio

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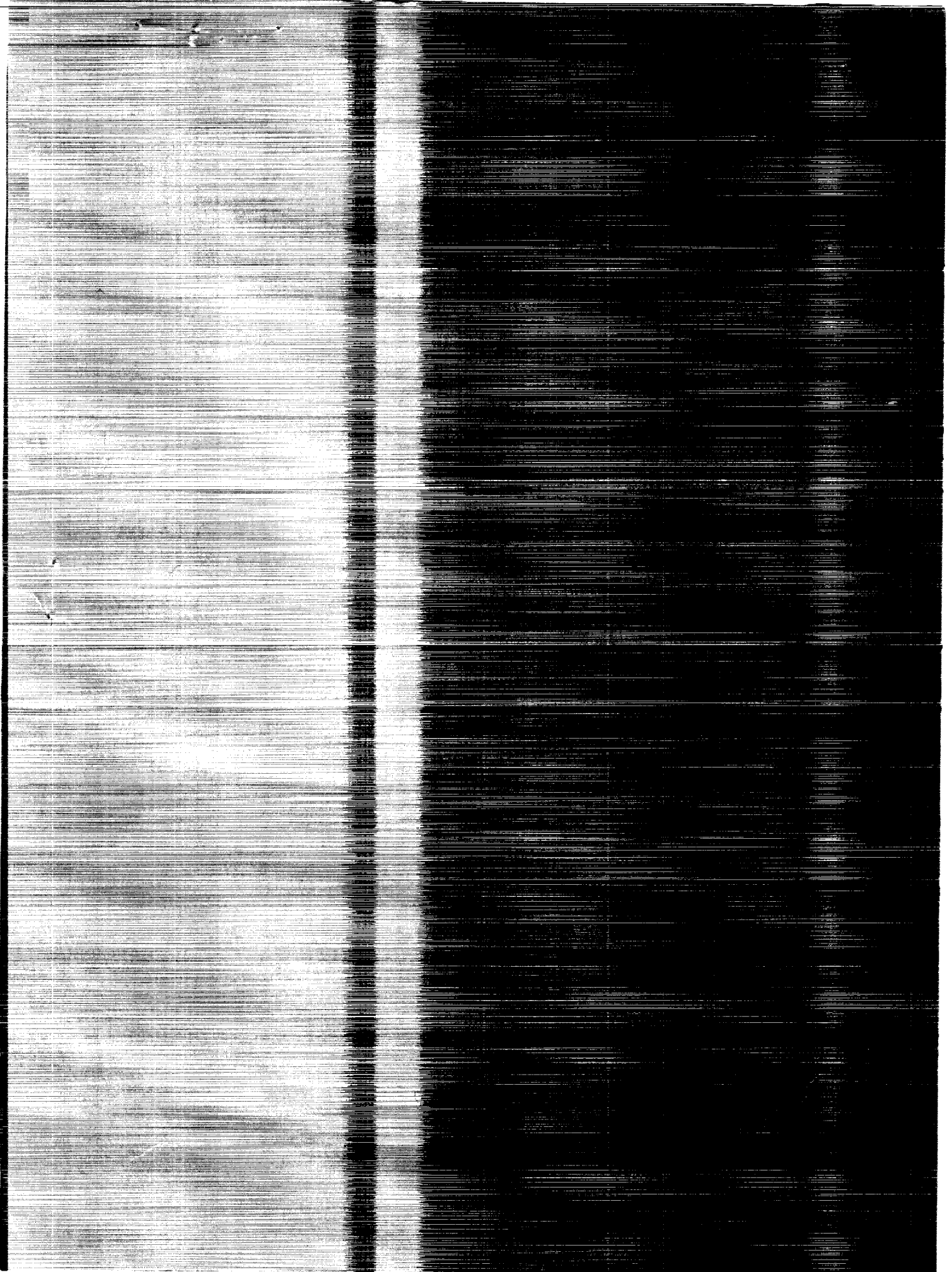
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AN EXPERIMENTAL INVESTIGATION OF THE RESTART AREA RATIO OF  
A MACH 3.0 AXISYMMETRIC MIXED COMPRESSION INLET

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# AN EXPERIMENTAL INVESTIGATION OF THE RESTART AREA RATIO OF A

## MACH 3.0 AXISYMMETRIC MIXED COMPRESSION INLET

by Glenn A. Mitchell and Robert W. Cubbison

Lewis Research Center

### SUMMARY

Restart area ratios were obtained for the test inlet from Mach number 2.5 to 3.0 and compared to ratios from other inlets. All inlets restarted with throat areas smaller than required by theory to pass the flow through a simple normal shock at the cowl lip.

Details of the unstarted inlet flow field were obtained at Mach 3. The unstarted inlet flow field was characterized by a separated region on the centerbody causing an oblique shock ahead of the throat. The size of the separated region was controlled by the inlet throat area, and the separation terminated at the throat station. The restart throat area was smaller than predicted because of the higher pressure recovery produced by the multiple shock structure.

### INTRODUCTION

Supersonic inlets with internal contraction are prone to "unstart" or regurgitate the internal supersonic flow and establish subsonic flow in the converging portion of the inlet. Restart of the inlet is accomplished by increasing the throat to entrance area ratio or by increasing the entering Mach number. Inlets utilizing a mixture of internal and external compression have been observed to restart with less throat area than the theoretical minimum value required to pass the flow through a normal shock at the cowl lip as predicted for one-dimensional flow in reference 1. Such restarts are associated with shock induced separation of the centerbody or compression ramp boundary layer, and reference 2 surmises that the improved restart characteristic is due to the increased pressure recovery produced by multiple shock waves in the resulting flow field. Further details are lacking. The present investigation was, therefore, undertaken to determine more of the details of the unstarted inlet flow field during the restart cycle of an axisymmetric mixed compression configuration.

## APPARATUS AND PROCEDURE

### Model and Configurations

The inlet used in this investigation was designed with the spike tip oblique shock on the cowl lip at Mach number 3.0, and employed a translatable  $20^\circ$  half-angle cone for off-design operation and to restart the inlet. At design conditions, 59 percent of the supersonic flow area contraction was external and 41 percent was internal. Figure 1 is a photograph of the inlet which had a 45.98 centimeter cowl lip diameter. The performance of this inlet was reported in reference 3.

The internal cowl angles were designed to intercept and turn the cone flow field toward the model centerline in two  $12^\circ$  steps. The resulting oblique shocks were focused on the model centerbody as shown in the bottom illustration of figure 2. An abrupt turn of the centerbody at this shock impingement point aligned the surface with the local flow. A flush bleed slot was located on the centerbody just forward of this impingement point to remove the spike boundary layer. This bleed air was ducted overboard through hollow support struts as shown in figure 2.

### Instrumentation

In addition to the standard instrumentation for mass flow and pressure recovery measurements (see ref. 3), six centerbody and cowl rakes were installed in the inlet aft of the cowl lip to determine pressure profiles of the internal flow from cowl lip to throat. As shown in the schematic representation of figure 3, four of the rakes were in the converging portion of the inlet and two were aft of the inlet throat. The rakes were not in a single peripheral location as suggested by figure 3 but were located at various circumferential positions to eliminate mutual interference. Both the centerbody and the inner surface of the cowl were instrumented with an axial row of static pressure taps. The investigation was conducted in the Lewis 10- by 10-foot supersonic wind tunnel at a Reynolds number of  $3.75 \times 10^6$  based on the inlet cowl lip diameter. Restart area ratios were determined at Mach numbers from 2.5 to 3.0. Details of the unstarted inlet flow field were obtained at Mach number 3.0 only.

## RESULTS AND DISCUSSION

The area ratios at which the inlet restarted are presented in figure 4 as a function of the average local Mach number at the cowl lip station just after restart. Data obtained from reference 2 and previously unpublished data from the inlet of reference 4 are shown for comparison. Each area ratio presented was computed from the geometric minimum area divided by the area perpendicular to the flow streamlines between the cowl lip and the spike surface. Because the average Mach number at the cowl lip station (rather than the free-stream Mach number) controls the theoretical limit of inlet internal contraction, it is therefore the proper correlating parameter. This local Mach number is a function of the free-stream Mach number and the

amount of external compression from the free-stream to the cowl lip. The area ratio curve for the isentropic compression limit is shown for comparison on figure 4. Also shown is the curve of the theoretical one-dimensional flow area ratio (ref. 1) required to pass the flow (restart the inlet) following a normal shock at the inlet cowl lip.

All of the inlets presented in figure 4 restarted at area ratios considerably smaller than predicted by the normal shock values. As expected, a consistent trend of lower starting area ratio with increased bleed was evident. The internal bleed flow at design conditions ranged from 0 to 6.3 percent of the inlet capture mass flow. All of the bleed areas were in the converging sections of their respective inlets. Figure 4 shows that even without bleed, the starting area ratio for all inlets would be clearly less than the normal shock curve. For example, at a cowl Mach number of 2.76, the no-bleed inlet restarted at an area ratio of 0.595 rather than the normal shock value of 0.737.

#### Observed Flow

In order to determine the cause of the observed discrepancy between theoretical and actual starting area ratios, data were obtained on the unstarted test inlet during the restart cycle at the inlet design Mach number of 3.0. The restart point of the inlet in this instance is represented by the dark symbol in figure 4. The slight increase in restart area ratio over the other test data for this inlet was probably caused by a thicker center-body boundary layer resulting from flow over a few circumferential slots located near the spike tip. These slots were present during this particular test but served no functional purpose for the results presented in this report.

Schlieren photographs of the inlet restart cycle are presented in figure 5. Figure 5(a) is a photograph of the started inlet on design and figure 5(b) shows the inlet unstarted at the same spike position. Figures 5(c) to (e) depict the unstarted inlet at increasing spike extensions. The inlet was just about to restart when the photograph shown in figure 5(e) was taken and a slight spike extension to that shown in figure 5(f) restarted the inlet. Flow separation on the cone surface was evident at all unstarted conditions. The oblique shock from the separated region was initially forward of the cowl lip (figs. 5(b) and (c)). As the spike was further extended, the separated region was reduced in size; and at restart (fig. 5(e)), the oblique shock from the separated region was well inside the cowl.

Enlarged photographs were used to determine that the oblique shock angle from the separated region was about  $35^\circ$  relative to the cone surface. The occurrence of separation is in agreement with the results of reference 5 in that the calculated cone surface Mach number of 2.3 produces a normal shock static pressure rise more than sufficient to induce flow separation. At this Mach number, the separation static pressure ratio of 1.89 observed in reference 5 requires an oblique shock angle of  $35.3^\circ$ , thereby corresponding closely to that measured from the photographs.

Profiles of the inlet flow field from the cowl lip aft to the throat were composed from measurements by the inlet total pressure rakes, the cowl and spike static pressures, and the schlieren photographs of figure 5. These profiles are presented in figure 6. Wall static and rake total pressures are all ratioed to free-stream total pressure, and lines of constant pitot pressure are indicated. The region of separated flow was defined as that containing pitot pressures lower than the highest measured spike static pressure. Figure 6(a) shows the inlet operating supercritically at the design spike position and corresponds to figure 5(a). The cone flow field was turned  $12^\circ$  by the initial internal cowl angle. The second cowl turn of  $12^\circ$  was placed relative to the first so that both of the resulting shocks impinged on the centerbody at the aft edge of the bleed slot. The increase in cowl static pressures following each turn resulted from three-dimensional flow effects.

Figures 6(b), (c), and (d) show the inlet unstated at successive spike extensions and correspond respectively to figures 5(b), between 5(c) and (d), and 5(e). Because of the forward movement of the cone shock with spike extension, it is not illustrated in figures 6(c) and (d). With the inlet unstated at the design area ratio (fig. 6(b)) the flow was characterized by a massive separated region (reverse flow region) which produced an oblique shock lying forward of the cowl lip and coalescing with the cone oblique shock. The separated region was reattached at the inlet throat at this spike extension and throughout the unstated portion of the restart cycle. Above the separated region was a region of turbulent mixing. It is the edge of this region that is seen in the schlieren photographs of figure 5. Shrinkage of the separated region with spike extension (as was noted in the photographs of fig. 5) is seen in figure 6 to result in a reduction in the amount of flow that passed through the separation-induced oblique shock.

#### Analysis of Observed Flow

Forward of the cowl lip. - The theoretical flow patterns presented in figure 7 were based on the unstated flow profiles of figure 6 and used the computed cone surface Mach number of 2.3 with the measured oblique shock angle to compute the subsequent flow regions. Without static pressure probes to determine the subsonic Mach numbers, it was assumed that the flow in region A<sub>II</sub> as well as A<sub>I</sub> (see fig. 7) attained subsonic speeds through a normal shock. Figure 7 is intended to be illustrative of the latter portion of the restart cycle wherein the separation-induced oblique shock tended to fall inside the inlet cowl. The point of separation shown in figure 7 was chosen to be between that of figures 6(c) and (d). There are three separate flow regimes entering the inlet pictured. An  $11^\circ$  region of separated flow lies on the cone surface. This region creates a  $35^\circ$  oblique shock aft of which is a Mach number 1.85 region. A subsequent normal shock produces a subsonic Mach number of 0.606 with a relatively high overall total pressure recovery ( $P/P_0$ ) of 0.72. Above the  $35^\circ$  shock, the undisturbed local flow passes through a single normal shock to a subsonic Mach number of 0.534 with a lower recovery ( $P/P_0$ ) of 0.54. The theoretical pressure recoveries of 0.72 and 0.54 are in good agreement with the measured values which averaged about 0.75 and 0.55 (figs. 6(c) and (d)). The throat area required for each unit mass rate of

flow is inversely proportional to its total pressure recovery. Therefore, a unit rate of flow from the higher recovery, multiple shock region required only  $0.54/0.72 \times 100$  percent or 75 percent of the throat area necessary to pass a unit rate of flow from the lower recovery, single shock flow field.

Aft of the cowl lip. - Because of the existence of two regions of dissimilar total pressure in the unstarted inlet (figs. 6(c) and (d)) both streams could not have been sonic at the geometric throat. The static pressures shown at the throat in figures 6(c) and (d) suggest that the upper region is sonic and the lower is supersonic. Evidently, the concept of a simple sonic throat is not an adequate description of the choking mechanism. Inasmuch as the area required to pass the flow of both streams would vary with the static pressure level, a series of computations were made to determine the static pressure level which would yield a minimum area. The variation of  $A/A^*$  across the throat was determined from the static to total pressure ratio obtained from the measured total pressure profile of figure 6(d) and an assumed uniform static pressure across the duct. From the variation of  $A/A^*$  across the throat an average value of  $A/A^*$  was determined for each assumed throat static pressure. Results are presented in figure 8. The static pressure providing the minimum average  $A/A^*$  ( $0.315 P_0$ ) was near the measured throat static pressure levels and the corresponding area was only 1.3 percent greater than that required by sonic flow in both streams.

Although the inlet geometric throat was not choked in the normal sense, it, nevertheless, appeared to be controlling the unstarted flow field. Under these conditions, the separated flow was observed to be stable and therefore amenable to measurement. As previously noted from figure 6, the separated region reattached at the inlet throat. This fact, coupled with a knowledge of the point and angle of flow separation, would define the shape and size of the separated region. Although the size of the separation (and the separation point) varied with spike extension, the flow area at the cowl lip station (between the separation zone and the cowl lip as observed from figs. 6(a), (b), and (c)) seemed to be a function only of the inlet throat area. Figure 9 corroborates the observations of figure 6; the size of the separated region at the cowl lip shrank with spike extension in such a manner that the geometric throat-to-cowl flow area ratio remained essentially constant at about 0.80. Thus the size of the separated region appeared to be controlled by the inlet geometric contraction ratio ( $A_{min}/A_{cowl}$ ) with the rear contour of the region being similar in shape to the internal cowl contour. No specific reason is evident as to why the flow area ratio tended to maintain a ratio of 0.80; but this value is between the normal shock restart area ratio,  $A^*/A$ , of 0.85 and 0.78 for the two flow regimes entering the inlet.

Because the throat to cowl flow area ratio was nearly constant, the following simple technique could be used to approximate the surface of the separated region at any unstarted spike extension:

(1) The extent of the separated region at the cowl lip station is obtained by constructing a cowl lip flow area equal to  $1/0.8$  (or 1.25)  $A_{min}$ , using the cowl lip as the outer boundary.

(3) The reattachment is a faired line downstream from the cowl lip station to the inlet throat.

The geometric inlet area ratios ( $A_{\min}/A_{\text{cowl}}$ ) are presented in figure 10 for spike extensions from the design position out to that at which restart occurred. The theoretical area ratios required to restart the inlet were computed from flow field measurements for various spike positions and are also shown in figure 10. These calculations were adjusted for the estimated slot bleed of seven percent mass flow during the unstart cycle. The theoretical inlet entrance (or cowl lip station) flow conditions used in the calculations were those pictured in figure 7 for the two flow regimes. For spike positions from design out to an extension of 0.88 inlet diameter, the separation-induced oblique shock was forward of the cowl lip and all the flow dictating the theoretical starting area ratio passed through the oblique shock. With further spike extension, the shock retracted inside the cowl lip allowing the flow field above this oblique shock to enter the inlet. The area ratio necessary for restart then became a function of the two flow fields. The division of the flow regimes at the cowl lip was determined for purposes of calculation from the experimental data of figures 5 and 6. The method of calculating the theoretical (or required) area ratio is given in appendix B.

The geometric area ratio provided by the inlet (fig. 10) increased with spike extension. However, at spike extensions above 0.88 the calculated area ratio required to restart the inlet also increased because the overall pressure recovery decreased as the spike was extended. This resulted because the inlet was ingesting an increasingly larger proportion of the lower recovery flow regime as the spike was extended. The required area ratio increased at a slower rate than the inlet area ratio and restart occurred when the geometric area ratio matched the required ratio at a value of 0.666. This was well below the theoretical limit of 0.78 based on simple normal shock recovery.

The required restart area ratio curve of figure 10 was based on a detailed knowledge of the flow. Although the required restart area ratio was as low as 0.575 at small spike extension ratios, the corresponding geometric area ratios provided by the inlet were less than the required ratios and thus prevented restart. Enlarging the separated flow region by some artificial means at spike extensions greater than 0.88 would reduce the required starting area ratio by increasing the overall pressure recovery. Restart might then occur if the flow still reattached at the throat. Hence, the mechanical adjustment of inlet geometry to effect a restart may be simplified. However, since the size and shape of the separated region appeared to be controlled by the contraction ratio and internal inlet lines, artificial enlargement of the separation to favorably affect the inlet restart characteristics seems unlikely to succeed.

## SUMMARY OF RESULTS

Restart area ratios of a Mach 3.0 mixed compression-axisymmetric inlet were obtained at Mach numbers from 2.5 to 3.0 and compared to other inlet

## SUMMARY OF RESULTS

Restart area ratios of a Mach 3.0 mixed compression-axisymmetric inlet were obtained at Mach numbers from 2.5 to 3.0 and compared to other inlet data. Detailed measurements of the unstarted inlet flow field were made at Mach number 3.0. The following results were obtained:

1. The test inlet plus other inlets from cited references with either zero or varying amounts of internal bleed restarted with throat areas smaller than required to pass the flow through a simple normal shock at the cowl lip. This occurred because shock-induced boundary layer separation, which was observed on the centerbody of the test inlet at all unstarted flow conditions, created a multishock system at the cowl lip capable of higher than normal shock pressure recovery. Prior to restart, the inlet flow field was composed of three regions: (a) a separated flow region on the compression surface, (b) a region aft of the  $35^\circ$  oblique shock from the separated region, and (c) the undisturbed cone flow field above the oblique shock. The flow passing through the  $35^\circ$  oblique shock experienced greater total pressure recovery than the flow in the cone flow field and required correspondingly less choked throat area, thereby lowering the overall inlet starting area ratio.

2. The inlet throat controlled the size of the separated flow region so that the region shrank as the spike was extended in such a manner that the throat-to-cowl flow area ratio remained nearly constant at a value of about 0.80. This shrinkage of the separated region reduced the proportion of higher recovery air entering the inlet and, thereby, increased the required geometric starting area ratio.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, December 18, 1967,  
720-03-01-62-22.

## APPENDIX A

### SYMBOLS

$A_{\text{cowl}}$	flow area at the cowl lip station bounded by the model geometry
$A_{\text{cowl flow}}$	flow area bounded by the cowl lip and the separated region
$A_{\text{min}}$	minimum internal flow area bounded by the model geometry
$A_{\text{th}}$	theoretical restart throat area
$d$	Inlet lip diameter
$M$	Mach number
$M_{\text{cone}}$	cone surface Mach number
$M_{\text{cowl}}$	average cowl lip station Mach number
$p$	static pressure
$P_0$	free-stream total pressure
$Re$	Reynolds number based on inlet cowl lip diameter
$x$	axial distance from spike tip to cowl lip

## APPENDIX B

### METHOD OF CALCULATING INLET RESTART AREA RATIO

The choked throat of the unstarted inlet controls the flow field upstream to the terminal shock. Restart will occur when the throat of the unstarted inlet will accept all of the flow from the supersonic field intercepted by the cowl under started conditions. The required restart area ratios were calculated for the measured flow fields shown in figure 6. Referring to figure 7, the theoretical restart throat area was determined as the sum of the two choked throat areas required to pass the flow through the measured cowl lip station areas  $A_I$  and  $A_{II}$ . The throat area for  $A_I$  is obtained by multiplying the measured  $A_I$  by the  $A^*/A$  for Mach 2.3 of 0.456 and dividing by the normal shock pressure recovery for Mach 2.3 of 0.583; or,

$$A_{Ith} = \frac{0.456}{0.583} A_I = 0.783 A_I$$

For  $A_{II}$ , the measured area is again multiplied by the  $A^*/A$  for Mach 2.3, but is now divided by the pressure recovery of 0.772 across the separation-induced oblique shock and the subsequent Mach 1.85 normal shock; or,

$$A_{IIth} = \frac{0.456}{0.772} A_{II} = 0.591 A_{II}$$

Therefore, the total required area is:

$$A_{th} = 0.783 A_I + 0.591 A_{II}$$

The throat area was modified for the estimated bleed mass flow of 0.07 by multiplying the theoretical restart throat area by 0.93. Therefore, the required minimum restart area ratio plotted on figure 10 is:

$$\frac{A_{min}}{A_{cowl}} = 0.93 \frac{A_{th}}{A_{cowl}}$$

This method does not account for the fact that the two streams would choke at different static pressures. This addition to the calculations would increase the minimum area only 1.3 percent in this case. The required restart area ratio calculated by the present method agreed well with the actual restart value of 0.666.

## REFERENCES

1. Kantrowitz, Arthur: Theory and Experiments on Supersonic Inlets and Diffusers. NACA Conference on Supersonic Aerodynamics, Ames Aeronautical Laboratory, June 4, 1946, pp. 36-50.
2. Watson, Earl C.: An Experimental Investigation at Mach Numbers from 2.1 to 3.0 of Circular Internal-Compression Inlets Having Translatable Centerbodies and Provisions for Boundary-Layer Removal. NASA TM X-156, 1960.
3. Obery, Leonard J.; and Stitt, Leonard E.: Performance of External-Internal Compression Inlet with Abrupt Internal Turning at Mach Numbers 3.0 to 2.0. NACA RM E57H07a, 1957.
4. Stitt, Leonard E.; and Salmi, Reino J.: Performance of a Mach 3.0 External-Internal-Compression Axisymmetric Inlet at Mach Numbers from 2.0 to 3.5. NASA TM X-145, 1960.
5. Nussdorfer, T. J.: Some Observations of Shock-Induced Turbulent Separation on Supersonic Diffusers. NACA RM E51L26, 1954.

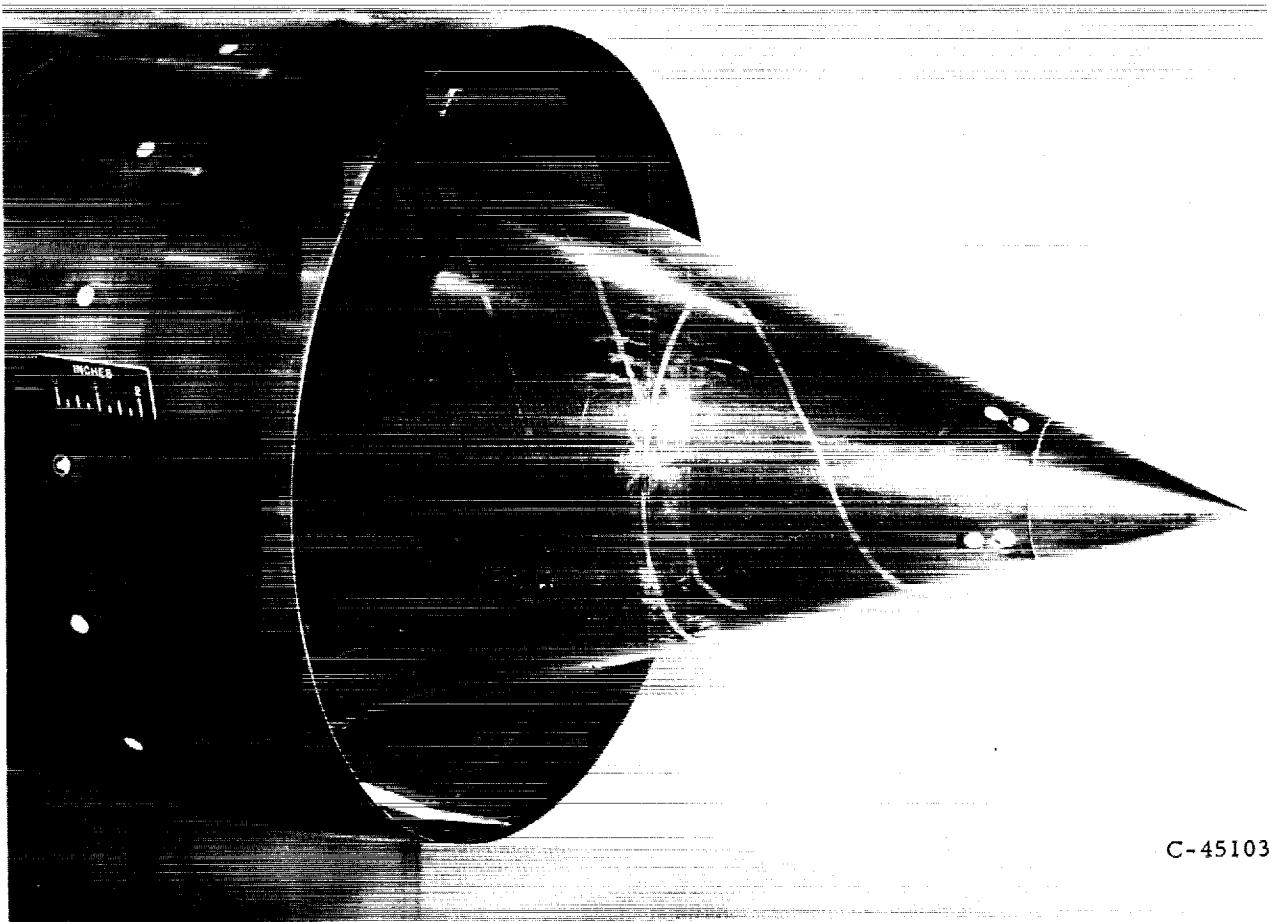
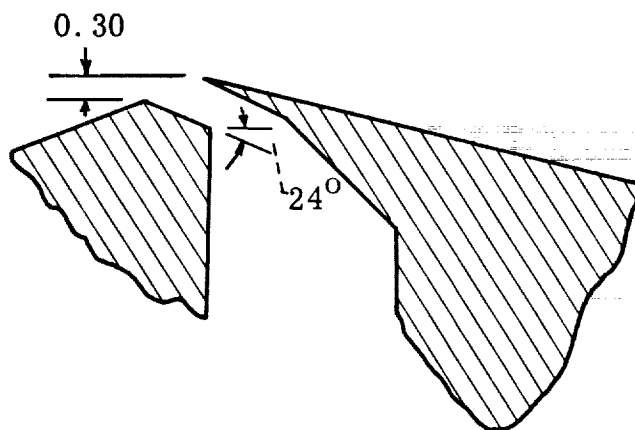
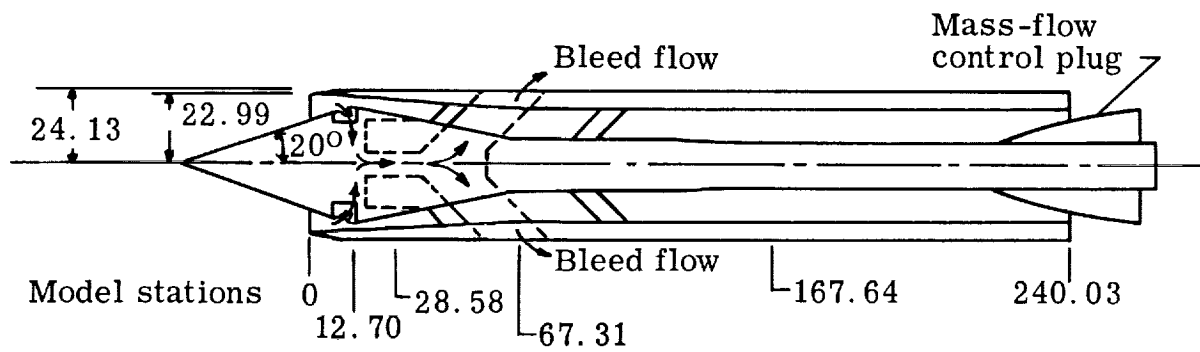
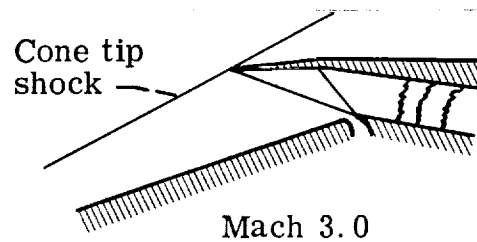


Figure 1. - Photograph of model with spike at design position.



Details of flush slot shoulder bleed



Theoretical shock location

Figure 2. - Model details. (All dimensions in centimeters.)

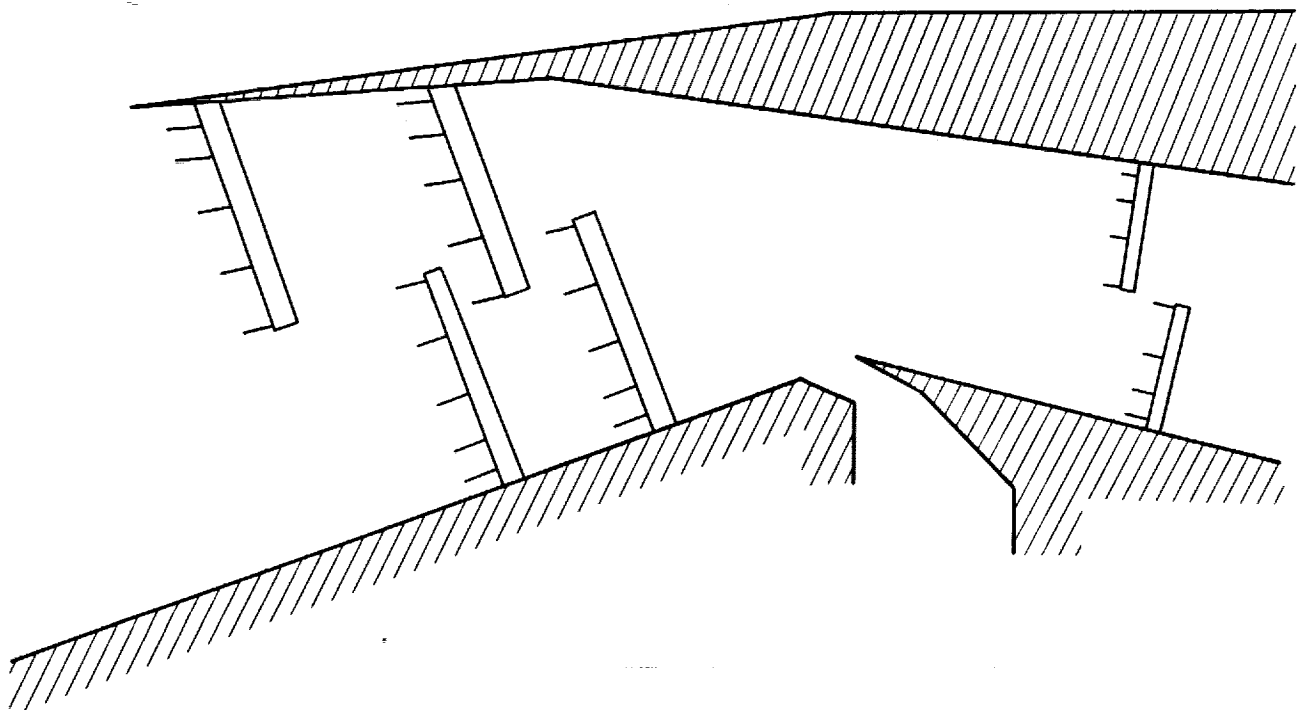


Figure 3. - Inlet total pressure rakes.

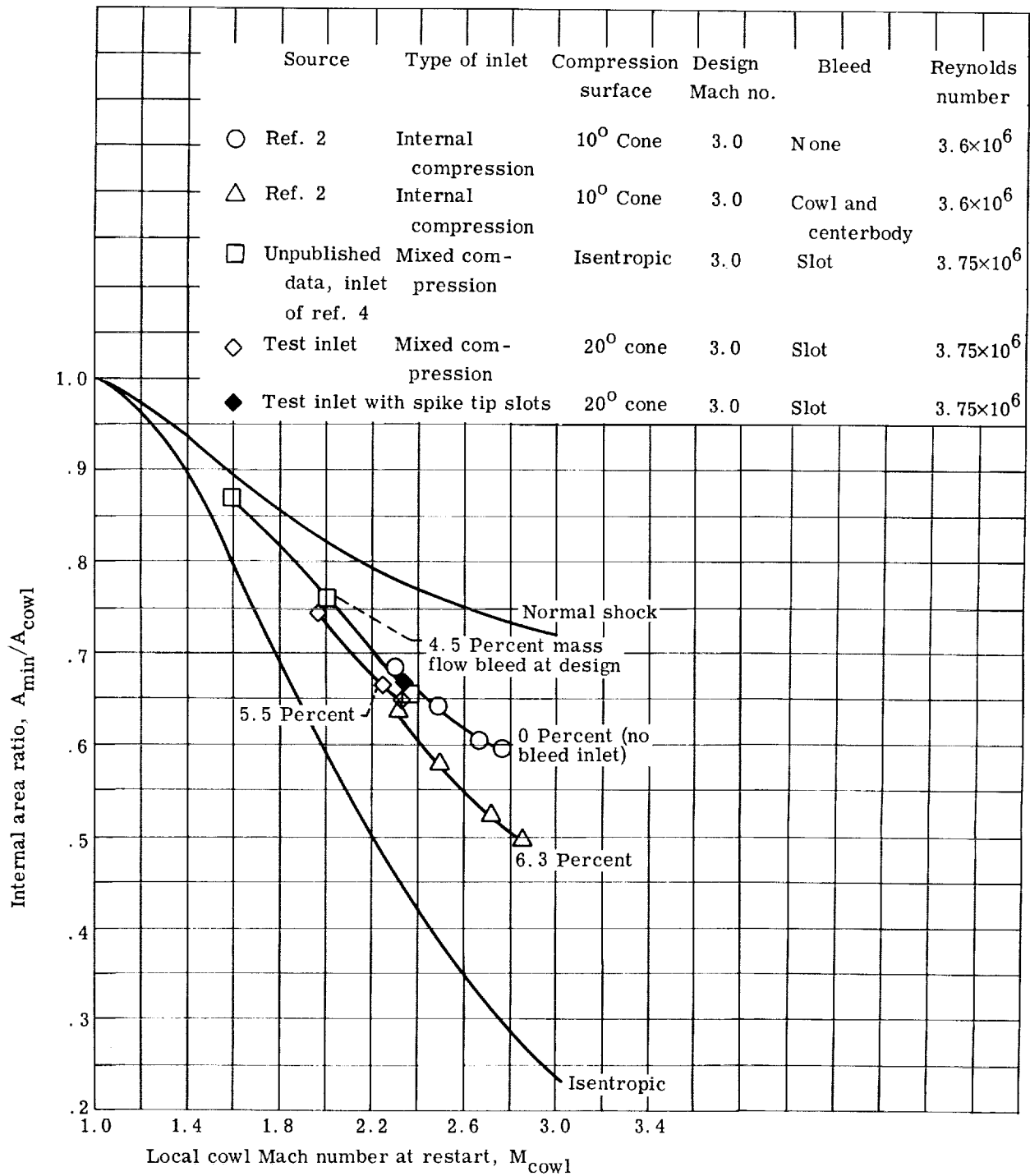


Figure 4. - Restart area ratios.



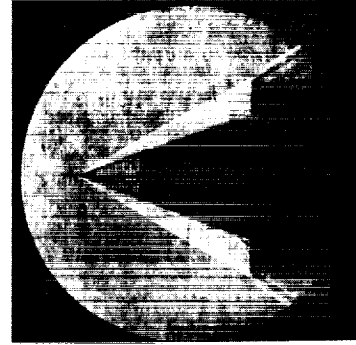
(a) Inlet started;  
 $A_{\min}/A_{\text{cowl}} = .502$ ;  
 spike extension,  $x/d = .862$ .



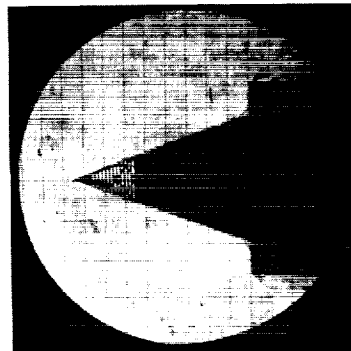
(b) Inlet unstated;  
 $A_{\min}/A_{\text{cowl}} = .502$ ;  
 spike extension,  $x/d = .862$ .



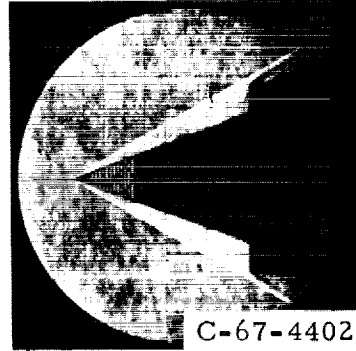
(c) Inlet unstated;  
 $A_{\min}/A_{\text{cowl}} = .561$ ;  
 spike extension,  $x/d = .896$ .



(d) Inlet unstated;  
 $A_{\min}/A_{\text{cowl}} = .631$ ;  
 spike extension,  $x/d = .930$ .

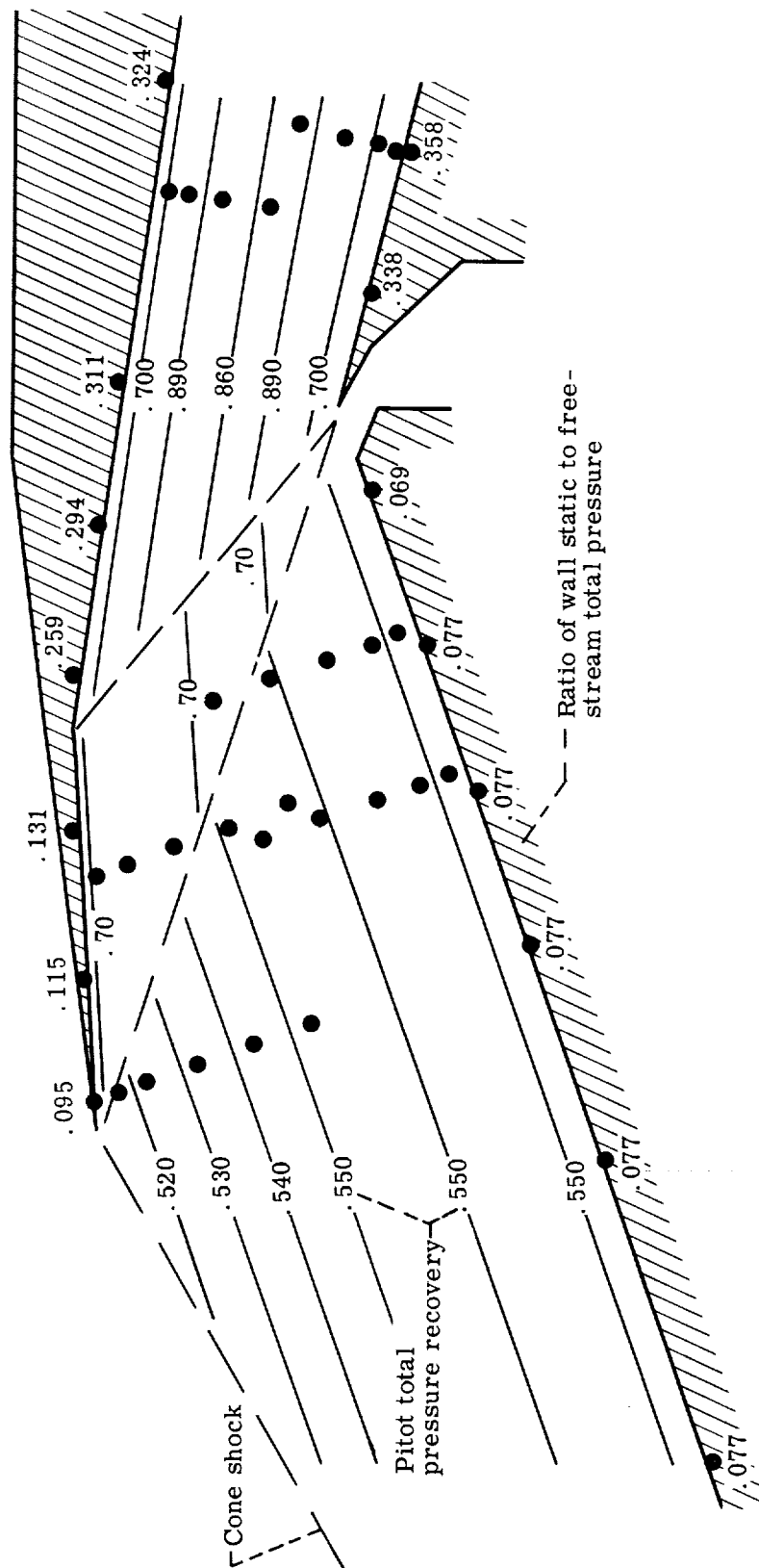


(e) Inlet unstated;  
 $A_{\min}/A_{\text{cowl}} = .662$ ;  
 spike extension,  $x/d = .943$ .



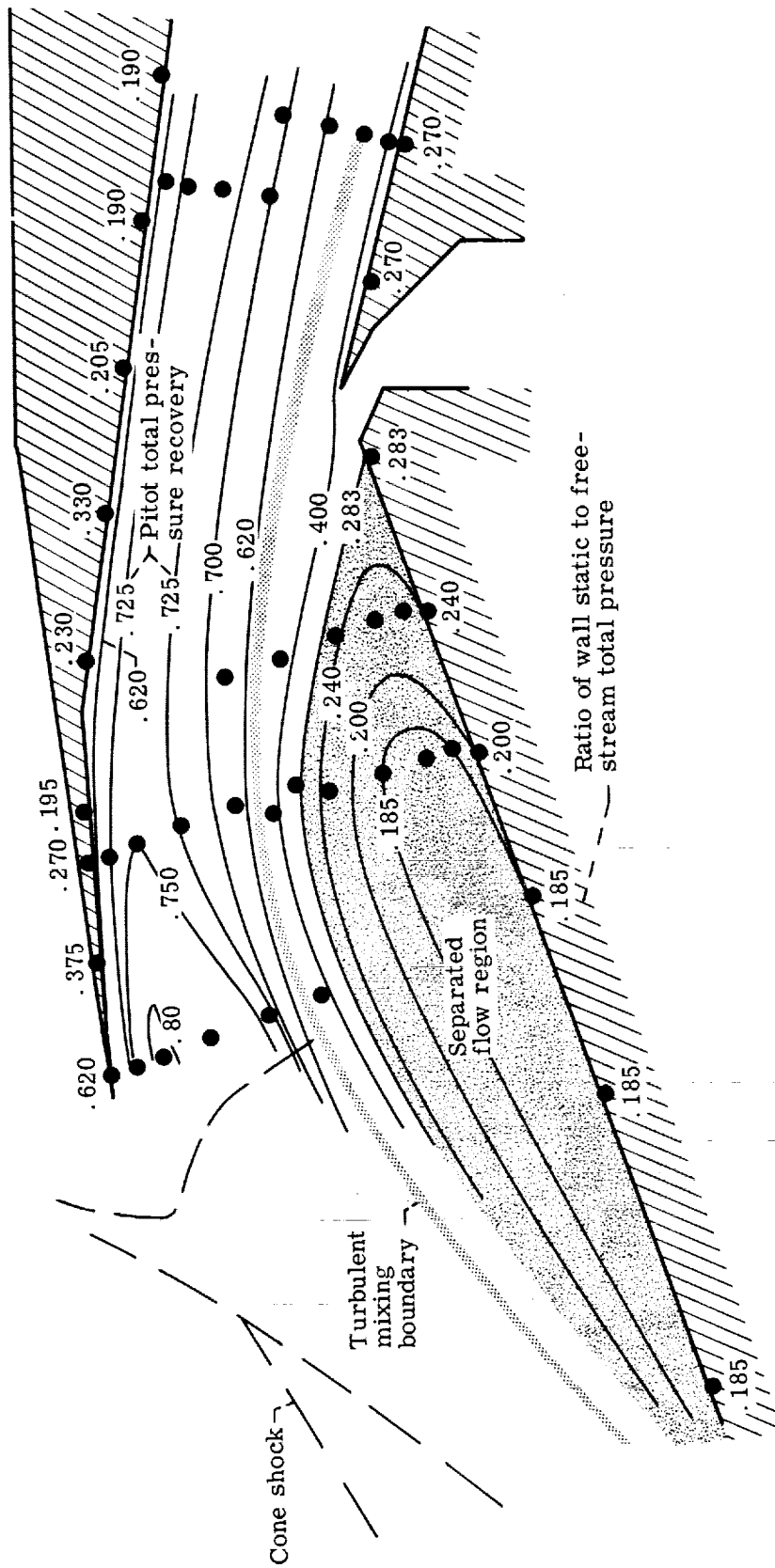
(f) Inlet started;  
 $A_{\min}/A_{\text{cowl}} = .666$ ;  
 spike extension,  $x/d = .945$ .

Figure 5. - Schlieren photographs of inlet restart cycle at Mach number 3.0.



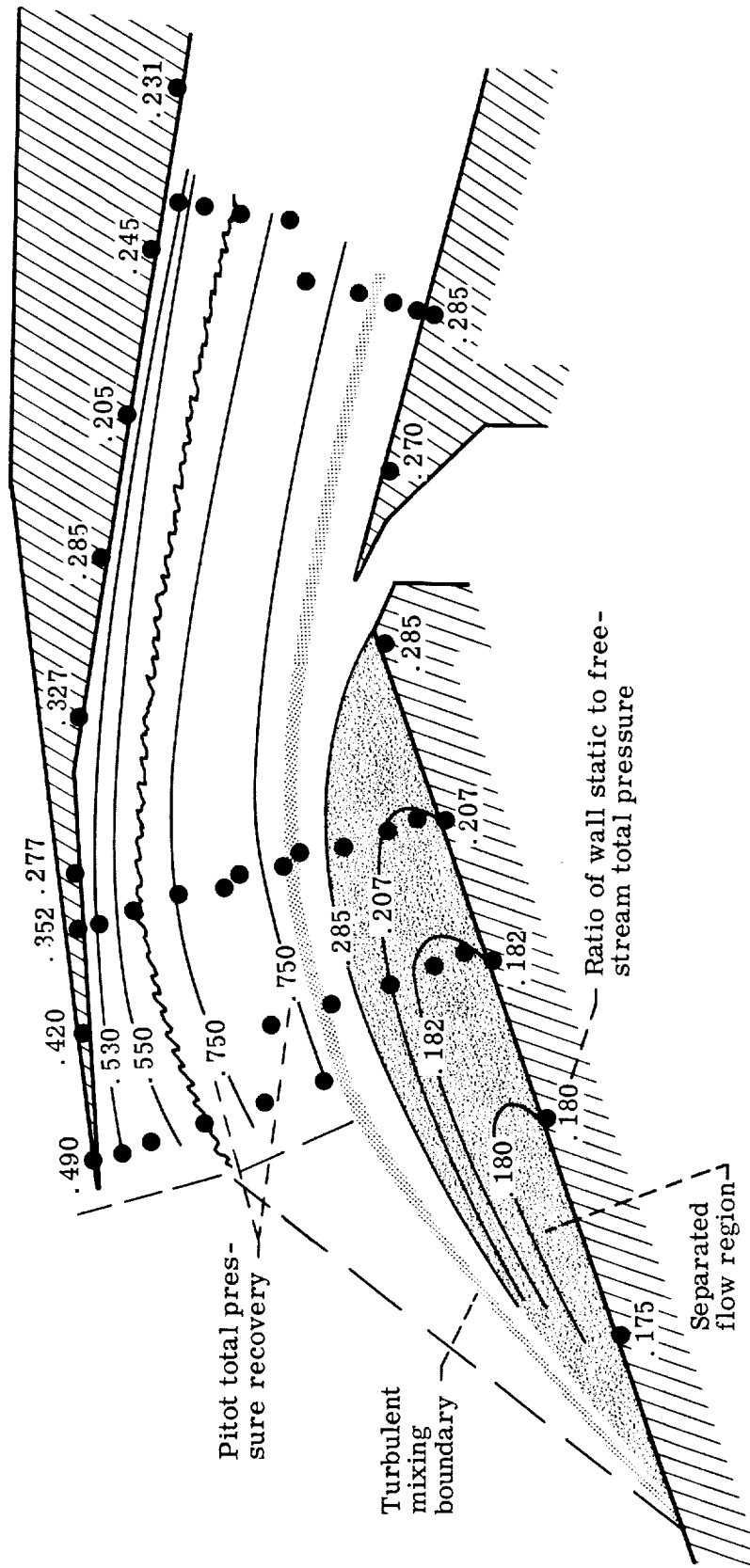
(a) Inlet started;  $A_{\min}/A_{\text{cowl}} = 0.502$ ; spike extension,  $x/d = 0.862$ .

Figure 6. - Inlet flow profiles at Mach number 3.0.



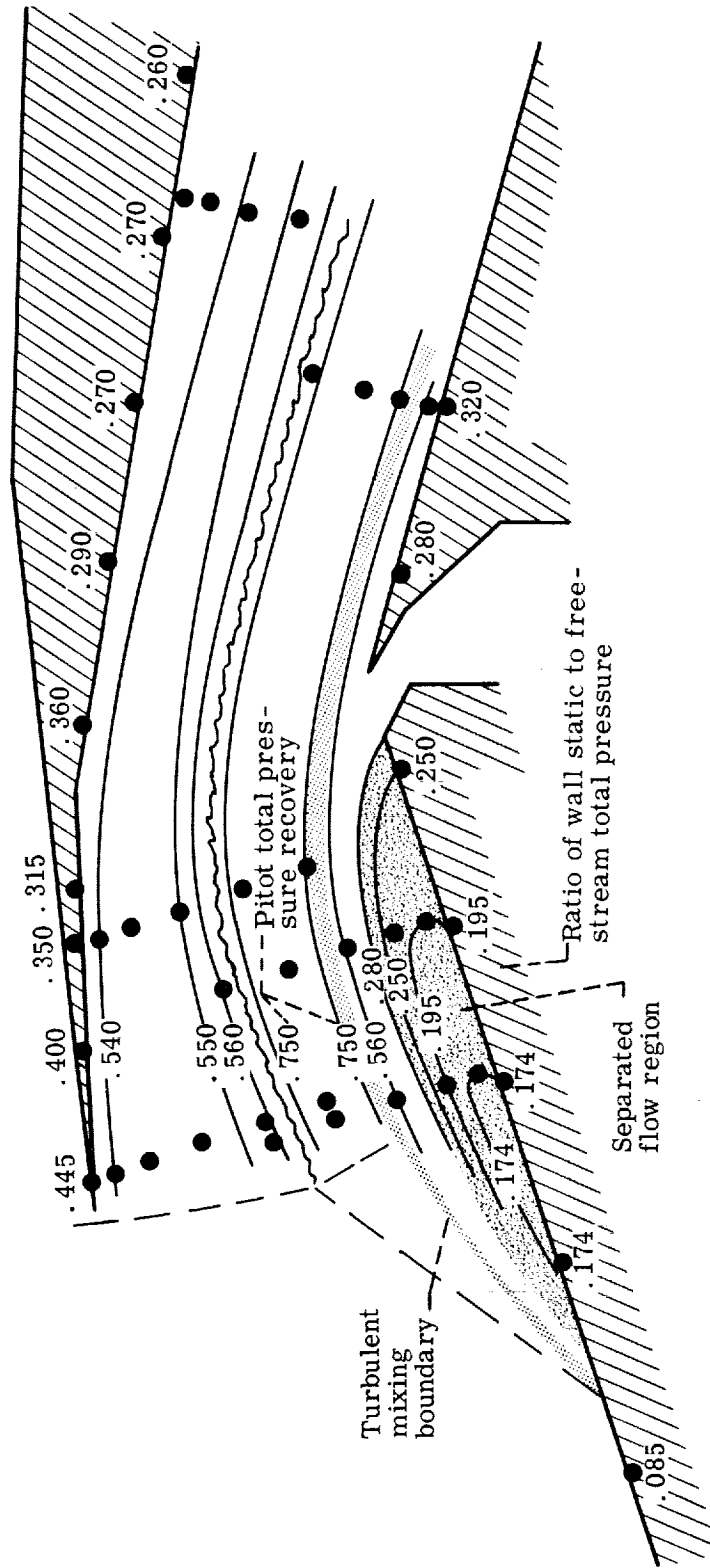
(b) Inlet unstated;  $A_{\min}/A_{\text{cowl}} = 0.502$ ; spike extension,  $x/d = 0.862$ .

Figure 6. - Continued.



(c) Inlet unstarted;  $A_{\min}/A_{\text{cowl}} = 0.595$ ; spike extension,  $x/d = 0.913$ .

Figure 6. - Continued.



(d) Inlet unstalled;  $A_{\min}/A_{\text{cowl}} = 0.662$ ; spike extension,  $x/d = 0.943$ .

Figure 6. - Concluded.

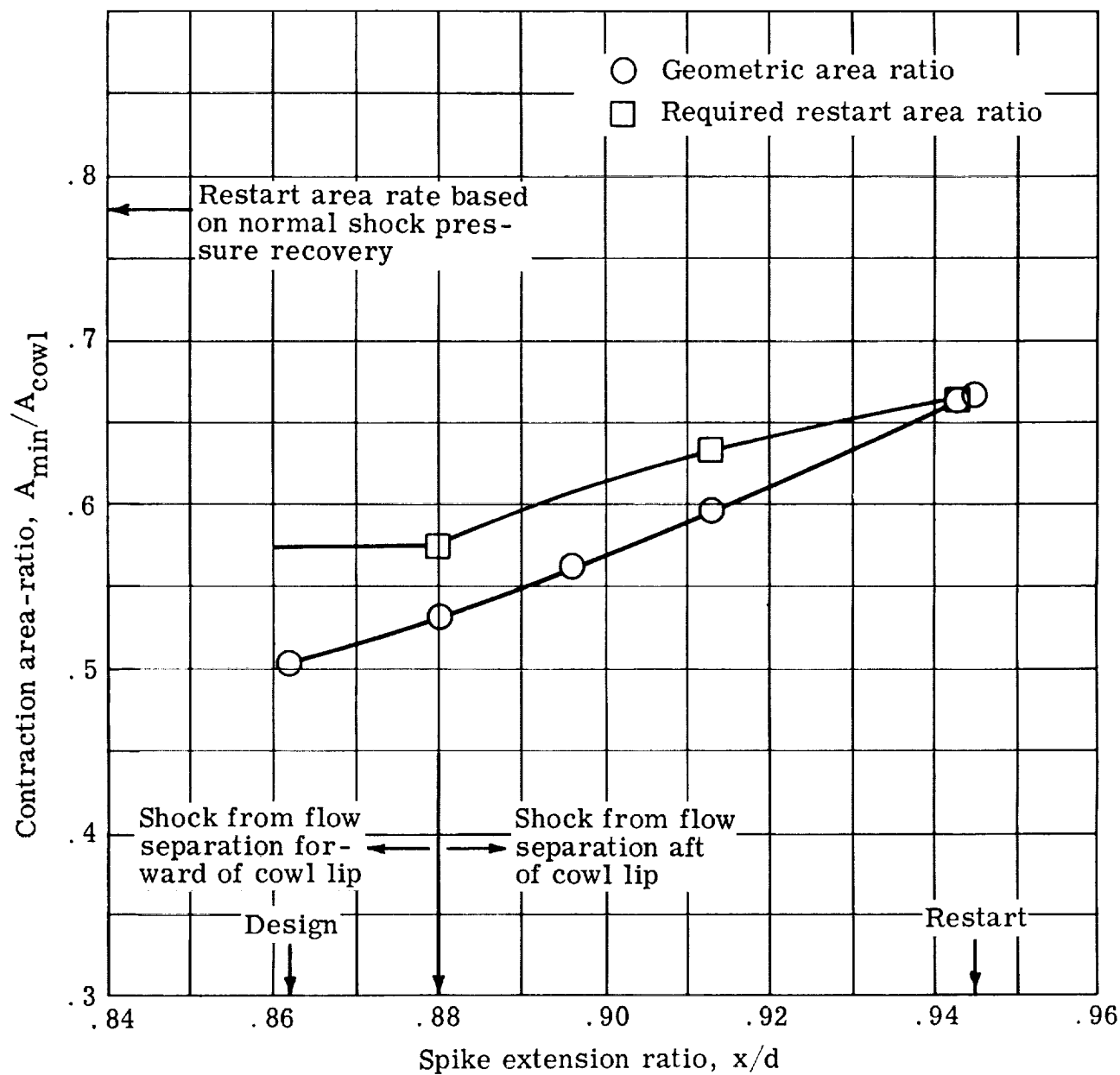
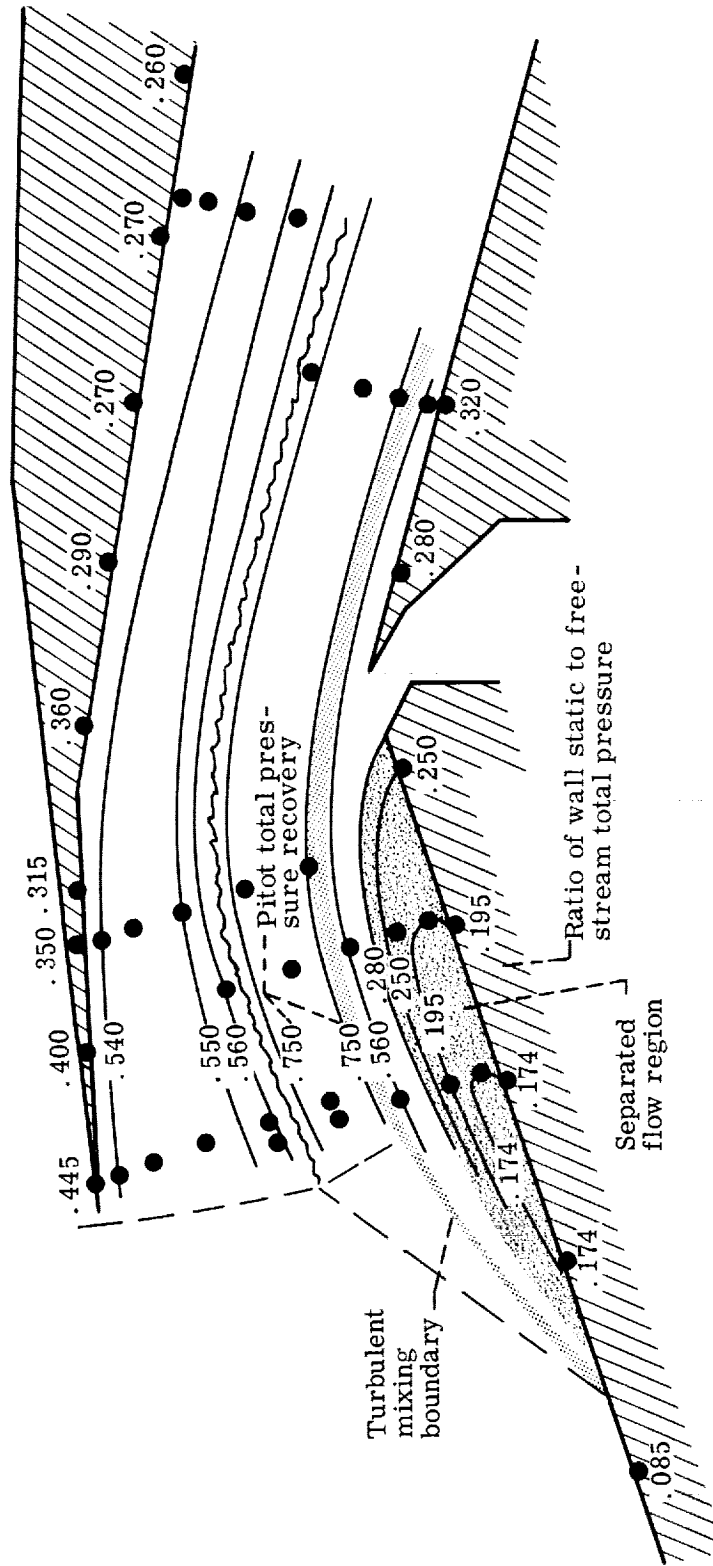


Figure 10. - Inlet area ratio variation with spike extension at Mach number 3.0.



(d) Inlet unstated;  $A_{\min}/A_{\text{cowl}} = 0.662$ ; spike extension,  $x/d = 0.943$ .

Figure 6. - Concluded.

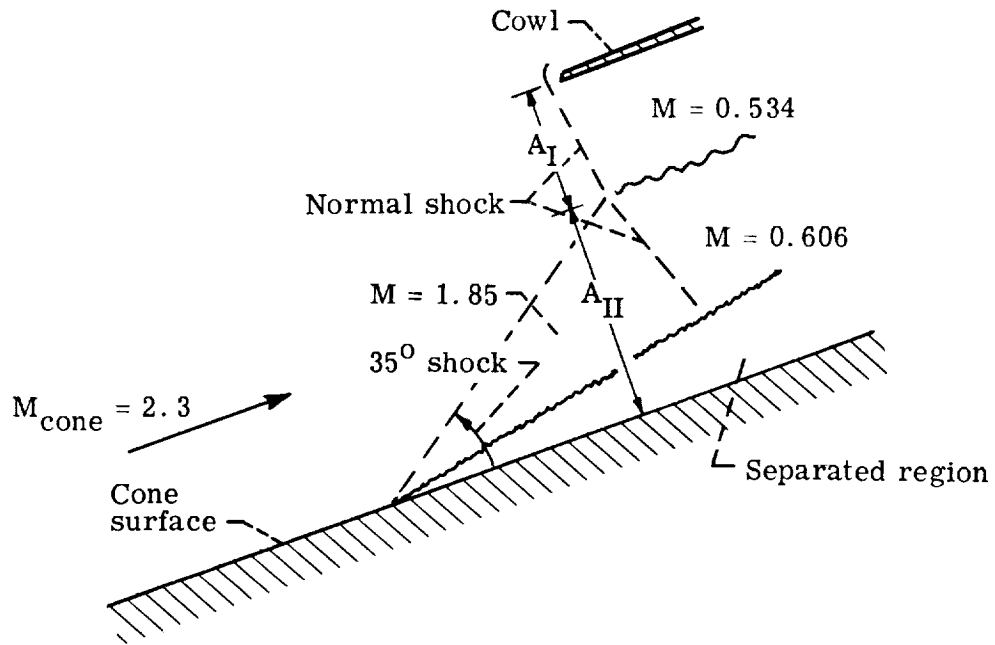


Figure 7. - Theoretical flow patterns of the unstarted inlet.

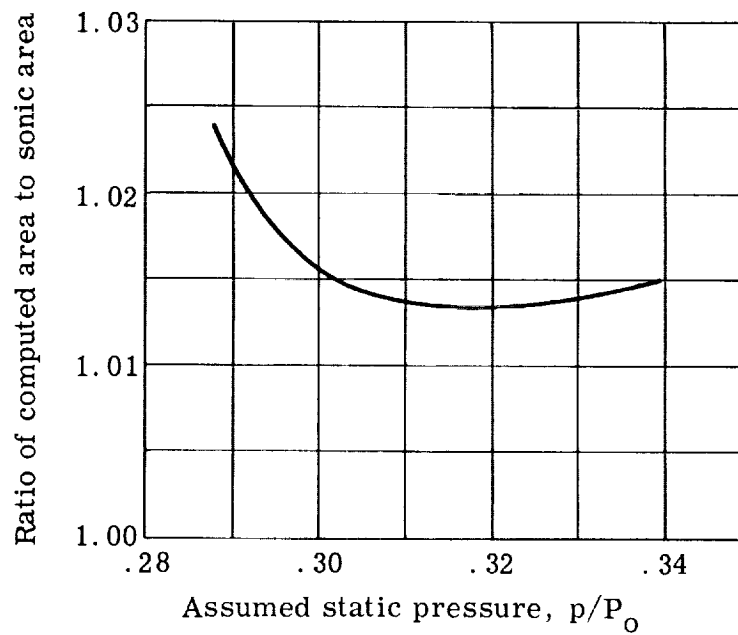


Figure 8. - Theoretical minimum area required for the unstarted inlet at Mach number 3.0;  $A_{\text{min}}/A_{\text{cowl}} = 0.662$ ; spike extension,  $x/d = 0.943$ .

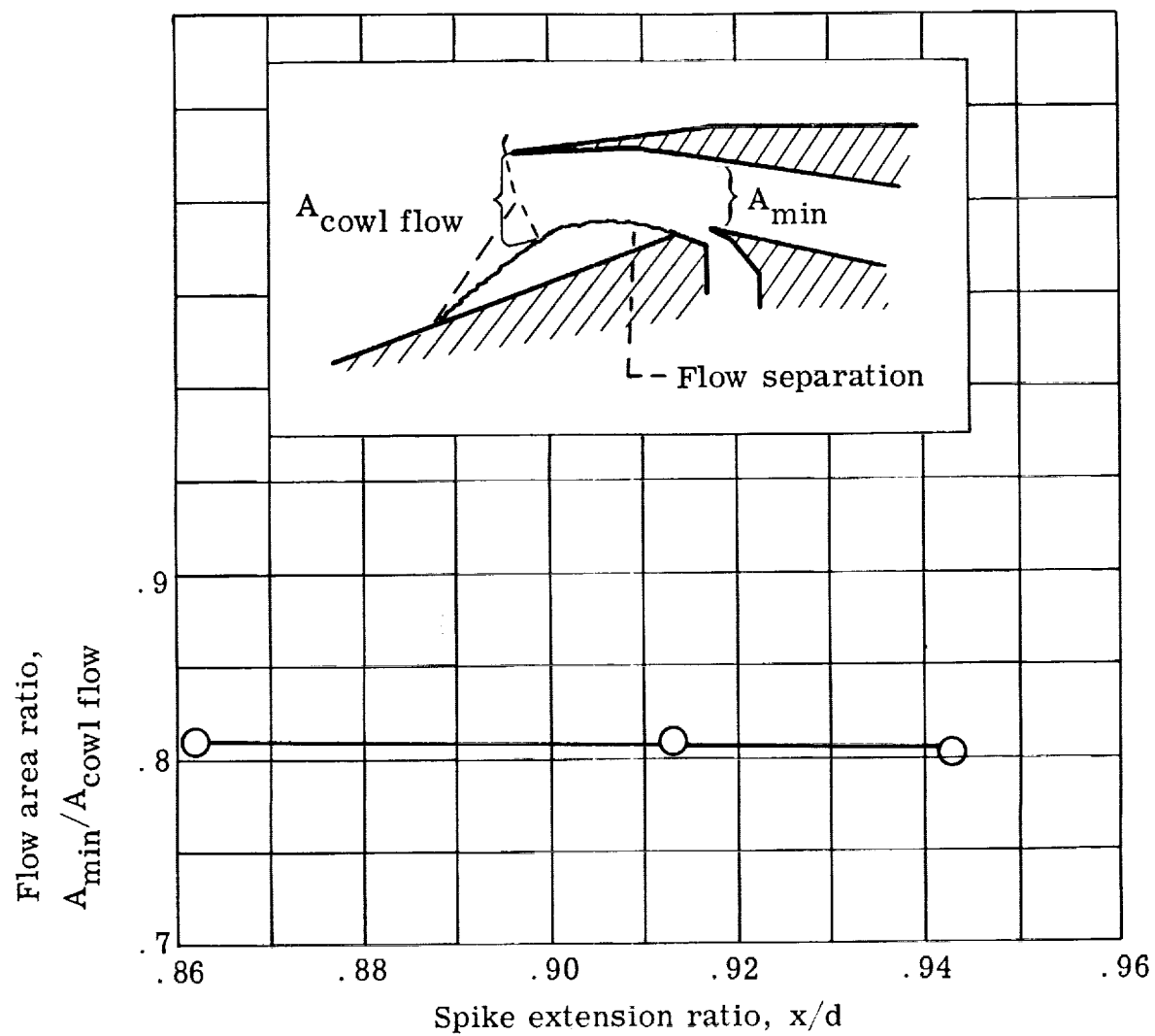


Figure 9. - Inlet flow area ratio variation with spike extension at Mach number 3.0.

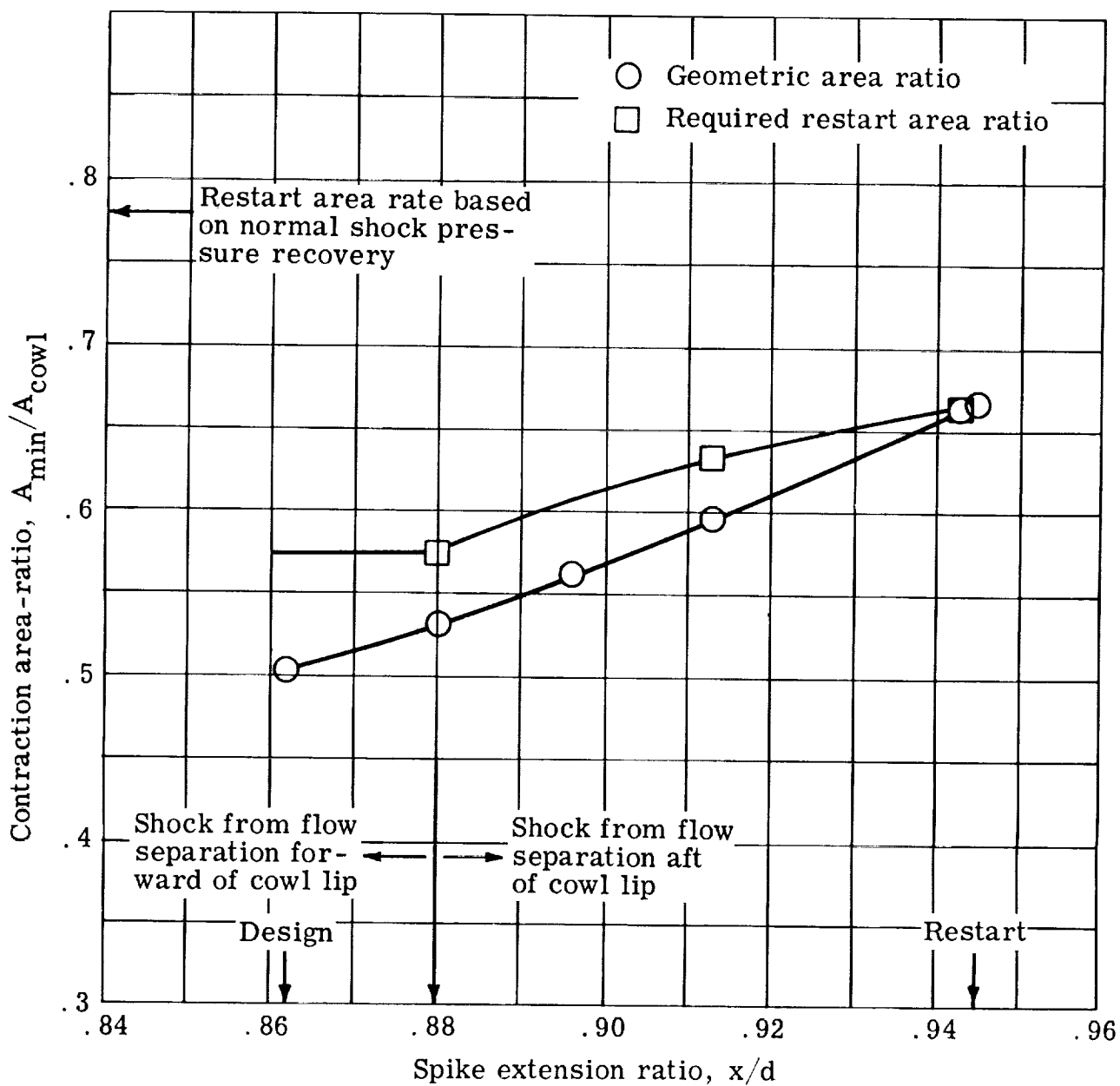


Figure 10. - Inlet area ratio variation with spike extension at Mach number 3.0.

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April 1968

Page 5: The second item of the series at the bottom of the page should read  
(2) The separation cone upstream of this station is that necessary to  
generate a  $35^{\circ}$  shock at the cone Mach number of 2.3.

Page 22, figure 10: The label near the upper left corner should read "Restart  
area ratio based on normal shock pressure recovery."

